A Multiscale Nested Modeling Framework to Simulate the Interaction of Surface Gravity Waves with Nonlinear Internal Gravity Waves

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LONG-TERM GOALS

Our long-term goal is to develop a multiscale nested modeling framework that simulates, with the finest resolution being sub-meter scale, surface mixed layer processes arising from the combined action of tides, winds, and mesoscale currents. We will focus on studying surface gravity wave evolution and spectrum in the presence of surface currents caused by strongly nonlinear internal solitary waves. We aim at understanding the impact of tidal, seasonal, and mesoscale variability of the internal wave field and how it influences the surface waves.

OBJECTIVES

This project aims at using a novel multiscale nested modeling framework to simulate, with the finest resolution being 10 cm scale while using inputs from 1000 km scale, surface mixed layer processes with an emphasis on the interaction of surface and internal waves. As a model problem of mixed-layer dynamics involving numerous physical processes acting over a wide range of spatio-temporal scales, we will focus on the interaction of surface and internal gravity waves in the South China Sea. We will seek answers to the following questions:

1) How does the wind-wave field evolve in the presence of surface currents driven by internal solitary waves?
2) How does the surface gravity wave field above internal solitary waves modify the mixing and dissipation in the mixed layer?
3) What specific parameters related to internal solitary waves enhance or limit their impact on the surface gravity wave spectrum? How does this affect the detectability of internal solitary waves in SAR imagery?
4) How does the variability of internal solitary wave currents impact the surface gravity wave spectra?

APPROACH

This project builds on a suite of novel and well established simulation tools developed by the PI and collaborators. At the finest scale, a large-eddy simulation (LES) code that simulates turbulence-wave interactions on a wave-surface-fitted grid and a nonlinear wave-field simulation code will be employed. The LES code will be driven by currents from a high-resolution, nonhydrostatic, isopycnal-coordinate model by collaborator Dr. Oliver Fringer at Stanford University that will simulate internal solitary wave evolution. Initial and boundary conditions for the latter will be obtained from collaborator Dr. Dong Ko at Naval Research Lab using the East Asian Seas Nowcast/Forecast System (EASNFS), which computes the generation of internal tides and includes assimilated seasonal and mesoscale variability. Ultimately, EASNFS is also nested within Global NCOM. As a result, while this project focuses on small-scale problems with domain size of 1 km and resolutions down to 1 m for turbulence eddies and 10 cm for waves, the fine-scale features are simulated through nesting of four models over spatial scales ranging from 1000 km down to 10 cm.

The LES code simulates turbulence near the sea surface on a wave-surface-fitted grid together with a phase-resolving wave-field simulation code. In the method, the grid evolves dynamically with the wave motion with the kinematic and dynamic sea-surface boundary conditions directly implemented. The LES uses advanced subgrid-scale (SGS) models, including a Lagrangian-averaged scale-dependent dynamic model for the SGS stress and a wave-kinematics-dependent dynamic model for the SGS sea-surface roughness in wind-and-wave interaction. As a result, turbulent eddies in the upper ocean and the sea surface deformation and roughness can be accurately captured in the simulations, with a grid resolution as fine as 1 m in a 1 km domain. Using the wave-field simulation code forced by LES, the resolution of surface gravity waves can be further increased to 10 cm wavelength.

The ocean wave field will be simulated using a novel wave-phase-resolving approach. Conventional wave prediction tools, called the third generation wave models including WAM, SWAN, WAVEWATCH, etc., are all based on formulations with the wave phases averaged. The three major processes in the wave dynamics, namely nonlinear wave interaction, wind input, and wave breaking dissipation, all depend heavily on the modeling of these processes. The existing empirical parameterizations are not suitable for many realistic, complex sea conditions, for which there exist inherent, fundamental difficulties for the traditional phase-averaging approach to further improve. Our wave-phase-resolving method, on the other hand, is a pseudo-spectral method based on the Zakharov formulation of velocity potential and coupling of different wave modes. It accounts for nonlinear wave interactions up to any desired order M in wave steepness. This method is extremely efficient computationally, requiring a computational cost almost linearly proportional to M and the number of wave modes N. The method achieves an exponential convergence of the solution with respect to both M and N. As a result, nonlinear wave interactions can be captured directly in the simulation. Recently, PI Shen's research group has further included wave breaking dissipation model and wind forcing model. As such, all of the essential processes in ocean wave-field dynamics are captured directly in a physical, wave-phase-resolving framework in our simulation.

WORK COMPLETED

This project just got started in the middle of 2015. We had a kickoff meeting in June, and had good discussions with other NOPP project participants. The PI and collaborators Drs. Oliver Fringer and Dong Ko have made a good research plan for the project.

Despite the short duration into the project, substantial progresses have been made. Research performed includes:

- Development and improvement of numerical capability for the simulation of two-layer fluids.
- Investigation of the dynamical interaction between surface waves and internal waves.
- Preliminary analysis of the surface roughness variation induced by internal solitary waves.

RESULTS

Internal waves have long been found to be related to the surface roughness variations captured by satellite synthetic aperture radar (SAR). When an internal wave propagates beneath surface waves, it induces a current field near the surface, which leads to a change in the sea surface roughness. Furthermore, the velocity field resulted from internal and surface waves may have significant impact on the transport in the mixed layer. To understand the mechanism that governs the interaction between internal waves and surface waves, it is of great importance to develop a numerical framework which can accurately capture the complex processes.

By utilizing our highly accurate and efficient numerical models, we have designed and conducted a numerical experiment to investigate the effect of internal solitary waves (ISW) on the surface wave roughness. Figure 1 shows the surface elevation of a JONSWAP wave field, the wave profile of an ISW, and the streamwise velocity distribution on a vertical plane. The simulation directly captures the two-way dynamical interaction between the internal and surface waves.

To further investigate the effect of ISW, the detailed velocity distribution is plotted in figure 2. As shown, there is a converging (resp., diverging) region above the leading (resp., trailing) edge of the ISW, in which the sea surface roughness associated with the surface waves are changed dramatically. This simulation captures the important feature of smooth and rough zones at the sea surface for the first time in direct computation, and thus validates the accuracy and effectiveness of our model.

IMPACT/APPLICATIONS

This project addresses an essential component to the operational requirements of the Navy, the accurate predictions of motions and transport in oceans. Improved modeling capabilities of processes acting over many scales and understanding of interactions between surface waves and internal gravity waves improves predictive capability critical to naval operations in deep waters. This project also addresses a critical need for the analysis of field data for the Navy. We will used our simulations to study the measurement data collected in South China Sea from the extensive field studies by ONR in recent years. The simulation-based analysis will be invaluable for the interpretation of field data.

TRANSITIONS

The proposed work will lead to high-resolution simulations of internal solitary wave evolution in three dimensions in realistic ocean settings. These simulations will lead to accurate wave-phase- and turbulence-resolving simulations of surface waves and knowledge of how they evolve in the presence of three-dimensional spatio-temporally variable surface currents. As a potential outcome of this

project, the remote sensing capability of the Navy will likely be improved. These results are likely to shed lights on how satellite SAR images are related to the dynamics of internal and surface waves.

RELATED PROJECTS

This project is part of the NOPP program "Seamless Forecasting from the Deep Ocean to the Coast." Our work is performed in close collaboration with Dr. Oliver Fringer at Stanford University and Dr. Dong Do at Naval Research Laboratory.

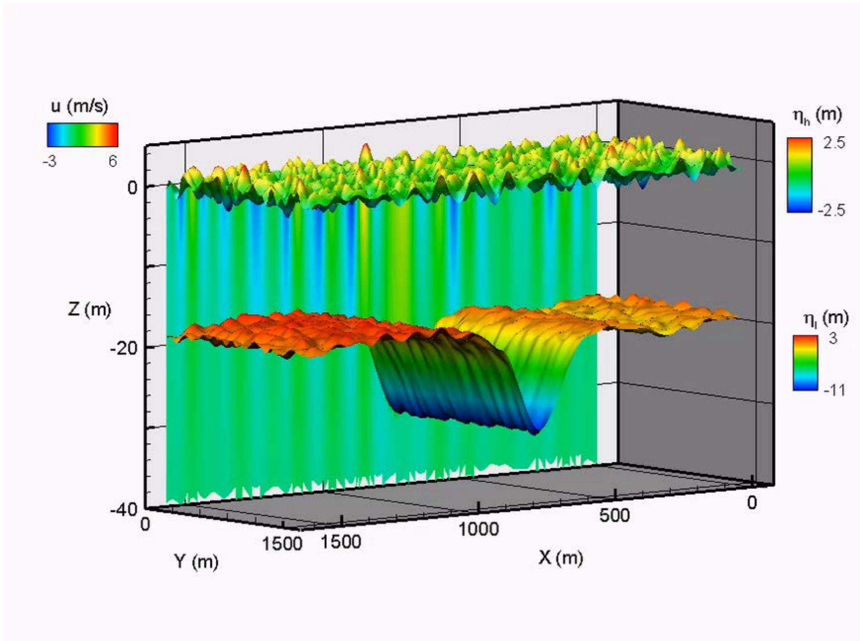

Figure 1. Surface elevation of a JONSWAP wave field and the wave profile of an internal solitary wave. The distribution of streamwise velocity on a vertical plane is also plotted.

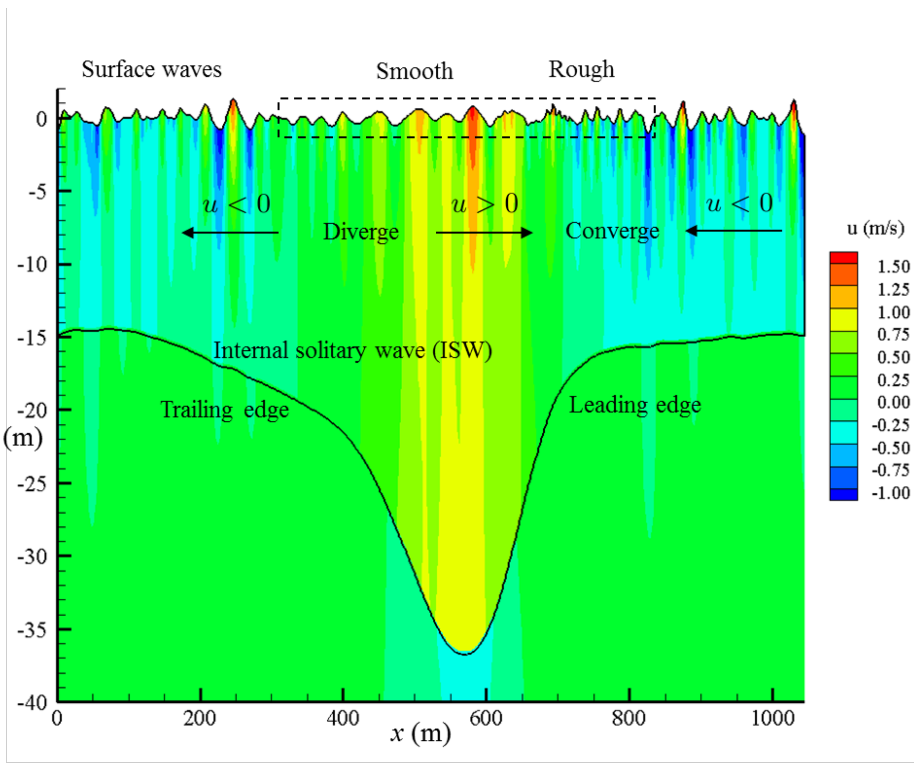

Figure 2. Distribution of streamwise velocity distribution on a vertical plane. The profiles of the surface waves and an internal solitary wave are also plotted. The surface waves and the internal wave propagate from left to right. Above the internal wave, the smooth and rough zones at the sea surface are dynamically captured in the simulation.